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Invited Review

Research on warehouse design and performance evaluation: A comprehensive review

Jinxiang Gu [a], Marc Goetschalckx [b,*], Leon F. McGinnis [b]

[a] Nestle USA, 800 North Brand Blvd., Glendale, CA 91203, United States
[b] Georgia Institute of Technology, 765 Ferst Dr., Atlanta, GA 30332-0205, United States

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ABSTRACT

This paper presents a detailed survey of the research on warehouse design, performance evaluation, practical case studies, and computational support tools. This and an earlier survey on warehouse operation provide a comprehensive review of existing academic research results in the framework of a systematic classification. Each research area within this framework is discussed, including the identification of the limits of previous research and of potential future research directions.

1. Introduction

This survey and a companion paper (Gu et al., 2007) present a comprehensive review of the state-of-art of warehouse research. Whereas the latter focuses on warehouse operation problems related to the four major warehouse functions, i.e., receiving, storage, order picking, and shipping, this paper concentrates on warehouse design, performance evaluation, case studies, and computational support tools. The objectives are to provide an all-inclusive overview of the available methodologies and tools for improving warehouse design practices and to identify potential future research directions.

Warehouse design involves five major decisions as illustrated in Fig. 1: determining the overall warehouse structure; sizing and dimensioning the warehouse and its departments; determining the detailed layout within each department; selecting warehouse equipment; and selecting operational strategies. The overall structure (or conceptual design) determines the material flow pattern within the warehouse, the specification of functional departments, and the flow relationships between departments. The sizing and dimensioning decisions determine the size and dimension of the warehouse as well as the space allocation among various warehouse departments. Department layout is the detailed configuration within a warehouse department, for example, aisle configuration in the retrieval area, pallet block-stacking pattern in the reserve storage area, and configuration of an Automated Storage/Retrieval System (AS/RS). The equipment selection decisions determine an appropriate automation level for the warehouse, and identify equipment types for storage, transportation, order picking, and sorting. The selection of the operation strategy determines how the warehouse will be operated, for example, with regards to storage and order picking. Operation strategies refer to those decisions about operations that have global effects on other design decisions, and therefore need to be considered in the design phase. Examples of such operation strategies include the choice between randomized storage or dedicated storage, whether or not to do zone picking, and the choice between sort-while-pick or sort-after-pick. Detailed operational policies, such as how to batch and route the order picking tour, are not considered design problems and therefore are discussed in Gu et al. (2007).

It should be emphasized that warehouse design decisions are strongly coupled and it is difficult to define a sharp boundary between them. Therefore, our proposed classification should not be regarded as unique, nor does it imply that any of the decisions should be made independently. Furthermore, one should not ignore operational performance measures in the design phase since operational efficiency is strongly affected by the design decisions, but it can be very expensive or impossible to change the design decisions once the warehouse is actually built.

Performance evaluation is important for both warehouse design and operation. Assessing the performance of a warehouse in terms of cost, throughput, space utilization, and service provides feedback about how a specific design or operational policy performs compared with the requirements, and how it can be improved. Furthermore, a good performance evaluation model can help the designer to quickly evaluate many design alternatives and narrow down the design space during the early design stage. Performance

* Corresponding author. Tel.: +1 404 894 2317; fax: +1 404 894 2301.
E-mail address: marc.goetschalckx@isye.gatech.edu (M. Goetschalckx).

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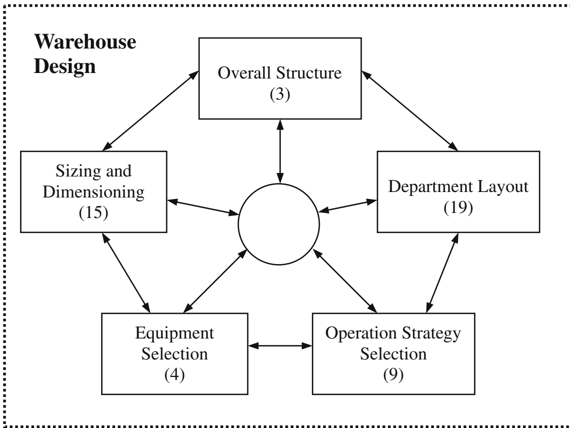

Fig. 1. Warehouse design problems and publication frequency.

evaluation methods include benchmarking, analytical models, and simulation models. This review will mainly focus on the former two since simulation results depend greatly on the implementation details and are less amenable to generalization. However, this should not obscure the fact that simulation is still the most widely used technique for warehouse performance evaluation in the academic literature as well as in practice.

Some case studies and computational systems are also discussed in this paper. Research in these two directions is very limited. However, it is our belief that more case studies and computational tools for warehouse design and operation will help to bridge the significant gap between academic research and practical application, and therefore, represent a key need for the future.

The study presented in this paper and its companion paper on operations, Gu et al. (2007), complements previous surveys on warehouse research, for example, Cormier (2005), Cormier and Gunn (1992), van den Berg (1999) and Rowenhorst et al. (2000). Over 250 papers are included within our classification scheme. To our knowledge, it is the most comprehensive review of existing research results on warehousing. However, we make no claim that it includes all the literature on warehousing. The scope of this survey has been mainly focused on results published in available English-language research journals.

The topic of warehouse location, which is part of the larger area of distribution system design, is not addressed in this current review. A recent survey on warehouse location is provided by Daskin et al. (2005).

The next four sections will discuss the literature on warehouse design, performance evaluation, case studies, and computational systems, respectively. The final section gives conclusions and future research directions.

2. Warehouse design

2.1. Overall structure

The overall structure (or conceptual design) of a warehouse determines the functional departments, e.g., how many storage departments, employing what technologies, and how orders will be assembled. At this stage of design, the issues are to meet storage and throughput requirements, and to minimize costs, which may be the discounted value of investment and future operating costs. We can identify only three published papers addressing overall structural design.

Park and Webster (1989) assume the functions are given, and select equipment types, storage rules, and order picking policies to minimize total costs. The initial investment cost and annual operational cost for each alternative is estimated using simple analytic equations. Gray et al. (1992) address a similar problem, and propose a multi-stage hierarchical approach that uses simple calculations to evaluate the tradeoffs and prune the design space to a few superior alternatives. Simulation is then used to provide detailed performance evaluation of the resulting alternatives. Yoon and Sharp (1996) propose a structured approach for exploring the design space of order picking systems, which includes stages such as design information collection, design alternative development, and performance evaluation.

In summary, published research on the design of the overall warehouse structure is limited to the use of rough approximations or qualitative models in combination with limited exploration of a design space, which itself may be restricted by simplifying assumptions. Two kinds of research contributions are needed: (1) principle-based assessment of appropriate decision aiding for these high level design decisions which are taken with uncertain knowledge of future operating conditions; and (2) simple, validated models that actually give results useful for guiding overall structural design.

As an aside, we note that there is a reasonably robust research literature on the general facility layout problem, see , e.g., Meller and Gau (1996). This research assumes the definition of the departments is given, and contemporary approaches remain challenged by the modeling of the department interactions, particularly material handling. Warehouse design, in contrast, is largely concerned with defining the departments, and a major issue in resolving that decision is to understand the interactions. Thus, at this point, the research on general facility design does not offer much to inform warehouse design.

2.2. Sizing and dimensioning

Warehouse sizing and dimensioning has important implications on such costs as construction, inventory holding and replenishment, and material handling. Previous research has been focused on a single storage department and treated the sizing and dimensioning decisions as two separate problems.

2.2.1. Warehouse sizing

Warehouse sizing determines the storage capacity of a warehouse. There are two scenarios in modeling the sizing problem: (1) Inventory levels are determined externally so the warehouse has no direct control over when incoming shipments will arrive and their quantities (e.g., in a third-party warehouse) and all the exogenous requirements for storage space have to be satisfied by the warehouse; and (2) The warehouse can directly control the inventory policy (e.g., an independent wholesale distributor). A major difference is that in the latter case, inventory policy and inventory costs should be considered in solving the sizing problem.

Assuming the warehouse has no control over inventory, warehouse sizing determines an appropriate storage capacity to satisfy the stochastic demand for storage space. White and Francis (1971) study this problem for a single product over a finite planning horizon. Costs considered include those due to warehouse construction, storage of products within the warehouse, and storage demand not satisfied by storage in the warehouse. Problems with either fixed or changeable storage size are modeled. The second model allows changes in the storage size over the planning horizon (e.g. by leasing additional storage space), so the decision variables are the storage sizes for each time period. A linear programming formulation is presented for the second model, and the optimal solution is found by solving a network flow problem (see also Lowe et al. (1979)). Similar problems of determining fixed and changeable warehouse size are also discussed by Hung and Fisk (1984) and Rao and Rao (1998) with different cost formulations.